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Title: UTILIZING EMISSION SPECTROSCOPY TO STUDY THE TIME-DEPENDENCE OF MIX

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Utilizing emission spectroscopy to study the time-dependence of mix

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Abstract

Emission spectroscopy has been incorporated into our suite of experimental diagnostic tools to study the time-dependence of pusher-fuel interface mix during the implosion of D_2 filled titanium-doped plastic inertial confinement fusion capsules. Titanium spectral emission data, in addition to X-ray gated imaging data and neutronics data, has been compared with results from one-dimensional Lagrangian radiation-hydrodynamics simulations utilizing the Scannapieco and Cheng fluid interpenetration mix model. The comparison showed differences especially in the relative intensities of the titanium lines that may indicate the need for changes in this simulation model. The comparison also demonstrated the potential usefulness of this experimental data set as a check on other mix models.

Keywords: Emission spectroscopy; Modeling; Pusher-fuel mix

1. INTRODUCTION

A good understanding of the time-dependent evolution of mix is important in many different dynamic systems, and emission spectroscopy can be an important experimental tool in probing that level of understanding. Of particular interest here is the time-dependence of pusher-fuel interface mix in inertial confinement fusion (ICF) capsules. The amount and the timing of pusher material reaching the center of fuel region can affect the yield of the capsule by at least an order of magnitude. Therefore, it is vitally important to understand how mix evolves during ICF capsule implosions to assist target designers in the simulation and design of optimized ICF ignition capsules.

Although emission spectroscopy has been previously used to study pusher-fuel interface mix, time-resolved spectral emission data has not been thoroughly employed to probe the amount and timing of the mix into the hot core of the imploded fuel that can reach temperatures of 3.5 – 4.5 keV. Indirect drive implosions utilizing emission spectroscopy were performed on the Nova laser to study pusher-fuel mix (Dittrich *et al.*, 1994), but the emission data was given only at the time of peak neutron yield production and thus provides no time-resolved data on the mix. Direct drive implosions utilizing time-resolved emission spectroscopy were performed on the OMEGA laser to study the amount and time-dependence of pusher-fuel mix (Regan *et al.*, 2002), but argon as the spectroscopic dopant could only probe the cool mantle of the fuel region. Because most of argon in the hot core of the imploded fuel is completely stripped of electrons, the argon emission spectra provide no specific information on this region of the fuel.

Our current research on ICF capsule mix utilizes a design with a thin layer of titanium-doped plastic at the pusher-fuel interface that mixes into the fuel with little titanium left in the pusher. A previous titanium-doped design to study the evolution of pusher nonuniformities near peak convergence (Smalyuk *et al.*, 2001) would not be appropriate for this study because most of the titanium that was doped into a thicker layer would remain in the pusher and interfere with the analysis of the emission spectra coming from the hot fuel. As will be discussed in more detail in the next two sections, the reason for using a spectroscopic tracer with a larger Z is to probe the amount and timing of pusher mix into the hottest portion of the fuel.

2. ICF CAPSULE DESIGN AND DIAGNOSTICS

We utilized a plastic ICF capsule design with an outer diameter of 860 microns and a wall thickness of about

20 microns. The capsules were filled with either 15 or 3 atmospheres of deuterium fuel in order to study pusher-fuel mix under very different hydrodynamic conditions. The unique aspect of this design was that it employed a very thin 0.1 micron layer of 4% atomic fraction titanium-doped plastic at the pusher-fuel interface. The reason for the thinness of this layer was to ensure that most of the titanium mixes into the deuterium fuel with very little left in the shell. Significant amounts of titanium left in the cold pusher would have attenuated the titanium emission spectrum through self-absorption effects as well as incorporating absorption features into the spectrum. This would have complicated the analysis of the relative intensities of the hydrogen-like and helium-like emission lines, the importance of which we will now discuss.

One of the main goals of this design was to obtain specific information on pusher mix into the hot core region of the imploded fuel. Titanium was chosen as a good spectroscopic probe of this mix for two important reasons. First, a sufficient population of hydrogen-like and helium-like titanium exists in the fuel for analysis of the emission lines intensities. Second, hydrogen-like alpha line emission requires temperatures observed in the hot core region of the fuel. This is shown in Figure 1 where a calculation with mix gives significantly more hydrogen-like alpha line emission than a clean calculation. Therefore, the comparison of the time-resolved hydrogen-like to helium-like titanium alpha line intensities provides useful information on both the amount and timing of pusher mix into hot core of the imploding fuel region.

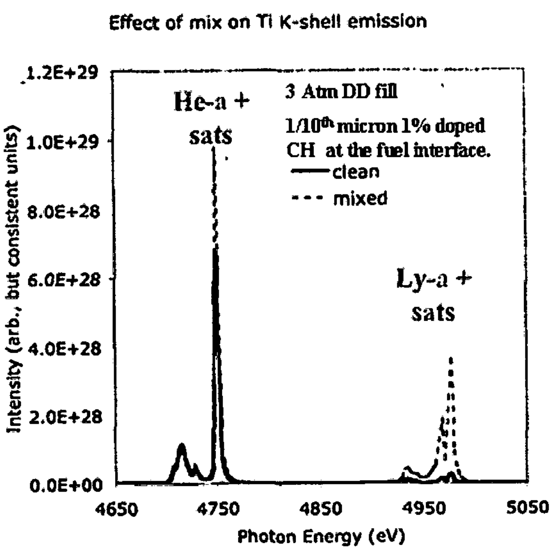

Fig. 1. This plot shows the intensities of both hydrogen-like and helium-like titanium alpha lines for a calculation with mix and a clean calculation. The deuterium fill pressure in this calculation is 3 atm.

Several diagnostics were fielded during the capsule implosion experiments. Spectral streak cameras (SSC's) were employed to gather time-resolved spectral emission data on the titanium helium-like and hydrogen-like alpha and beta lines in order to measure the relative intensities of these lines. Gated X-ray framing cameras (XRFC's) were used to image the capsules as they implode and to look for evidence of limb brightening, an indicator of the level of mix in the capsule at the corresponding times. Neutron diagnostics were employed to measure neutron flux and thus determine the neutron yield as well as the ion temperature in the deuterium fuel region. A charged particle spectrometer was employed to measure proton production from the capsule that provides unique measurements on secondary reactions due to fusion products in the deuterium fuel. These measurements could then be used to provide an independent determination of the temperature in the fuel region through the corresponding reaction rates.

3. RESULTS AND COMPARISONS

The ICF capsule implosion experiments in support of this research were performed on the on the OMEGA laser system in September 2003. The capsules were imploded with 60 beams of laser irradiation with a total energy on target of 22-23 kJ. Smoothing by spectral dispersion (SSD) was utilized to reduce laser hot spot imprinting on the ablation surface of the pusher. The resulting implosions appeared to be symmetric with no noticeable laser-driven features. The symmetry of the implosion was important in order to achieve the closest one to one comparison of experimental data results to the model simulation results.

Overall, the experiments provided useful information for our analysis. We obtained strong time-resolved hydrogen-like and helium-like titanium alpha emission lines from the SSC's. An example of the data is shown in Figure 2 for a capsule filled with 15 atmospheres of deuterium. For the purposes of this analysis, we will limit our discussion to data and simulation results on capsules with 15 atmospheres of deuterium fuel.

Before analyzing the time evolution of the spectral line energy outputs, a quantity directly related to the line intensities, a standard reduction of the data was first carried out. Film density was converted to exposure by the use of a film step wedge. Isotemporal curvature of the streak due to effects in the SSC's was removed from the data. Filtering as well as the conversion efficiency of the gold-plated photocathode in the SSC's affected the recorded emission intensity as a function of frequency and thus required a frequency-dependent correction to the streak intensity. The absolute timing of the streak data was set by looking for the onset of laser irradiation on an SSC with a slower streak speed. The time of maximum emission on the streak from this camera is then aligned to the time of maximum emission on the streak from the camera with the relevant data adjusting for the difference in the streak speed. The uncertainty in this technique is around 50 ps.

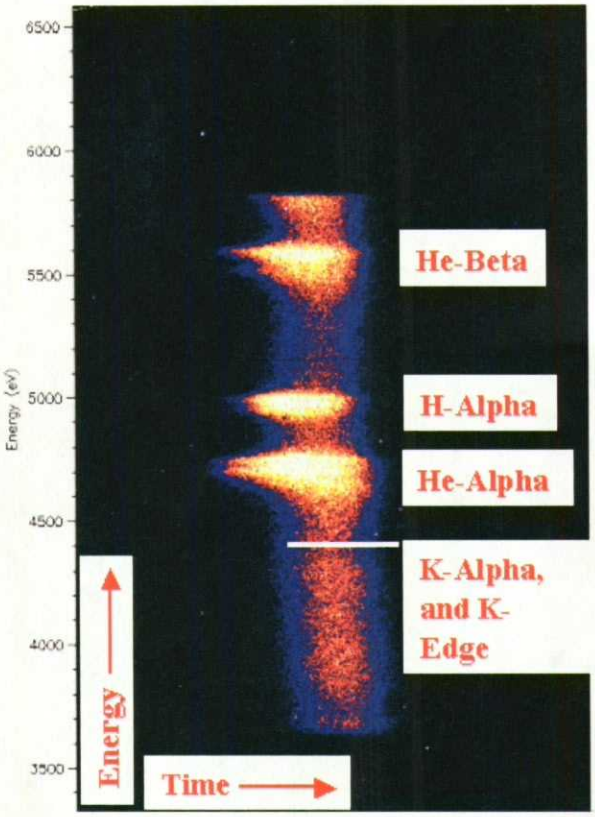

Fig. 2. This streak data from a 15 atm experimental shot shows strong emission of the hydrogen-like and helium-like titanium alpha lines as well as the helium-like titanium beta line.

Once these corrections were applied to the data, we then proceeded to analyze the time evolution of the energy outputs of the alpha lines. We did this by taking frequency lineouts through the streak at several different times and then summing up the area underneath each of the lines thus providing the energy output of the lines at the times corresponding to each lineout. From this data, we determined the ratio of the energy output of the hydrogen-like alpha line to the helium-like alpha line that would then be used as a measure of the amount and timing of pusher mix into the hot core region of the fuel.

Armed with this reduced data set from the experimental spectral data, we set out to test a specific mix model. We ran 1D Lagrangian hydrodynamic simulations utilizing the Scannapieco and Cheng mix model (Scannapico & Cheng, 2002 ; Wilson *et al.*, 2003) matching both the observed neutron yield production ranging over the values of $1.1 - 1.5 \times 10^{11}$ and a bang time of roughly 1.7 ns. The timing of the simulated implosion was controlled by the use of a flux limiter with a value of about 0.05. The yield was matched by adjusting the mix model parameters α and δ through a parameter study as is shown in Figure 3. The parameter α corresponds to the scaling of the eddy sizes, and the parameter δ corresponds to the diffusive mix length scale. For the simulated emission and gated image results shown here, we used an α of 0.09 and a δ of -1.0.

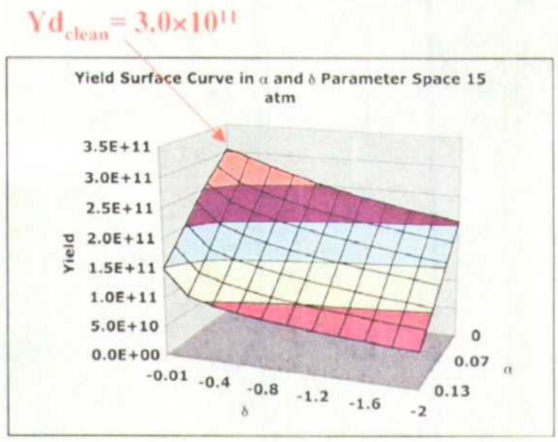

Fig. 3. This plot shows the neutron yield as a function of the mix parameters α and δ for a simulated implosion of a capsule with 15 atm of D_2. The value in the rear left corner is the clean yield value.

In order to generate a simulated titanium emission spectrum and the corresponding alpha line energy output ratios, we needed three sources of data. First, the electron density, electron temperature, and titanium number were extracted from all of the Lagrangian zones containing titanium in the hydrodynamic simulation as a function of time. Second, a titanium level population model was generated using the collisional radiative equilibrium transport atomic code CRETIN (Scott *et al.*, 1994) to provide the relative intensities of the titanium emission lines for the electron density and temperature ranges consistent with the imploding capsule. Third, Stark-broadened line shapes appropriate for the conditions expected in the imploding capsule were generated using the multi-electron radiator line shape code MERL (Woltz *et al.*, 1988; Mancini *et al.*, 1991; Junkel *et al.*, 2000). These three sets of data were read into a modified version of the spectral post-processing fitting code TIFIT to generate the simulated titanium hydrogen-like to helium-like alpha line energy output ratios.

Figure 4 shows a comparison of this ratio for a clean hydrodynamic simulation, a hydrodynamic simulation with the mix model included, and the experimentally determined ratio, all for an imploding capsule with 15 atmospheres of D_2 fuel. As expected, the simulation with the mix model included has more hydrogen-like alpha line emission than the clean simulation because the titanium is exposed to the hottest regions of the fuel. However, the simulation predicts less hydrogen-like alpha line emission than was observed coming from the imploding capsule. This indicates either that the mix model does not mix enough pusher material into the fuel core or the hydrodynamics simulation has another problem separate from the mix model. To differentiate between the possible causes, we look at other sources of data from the experiments.

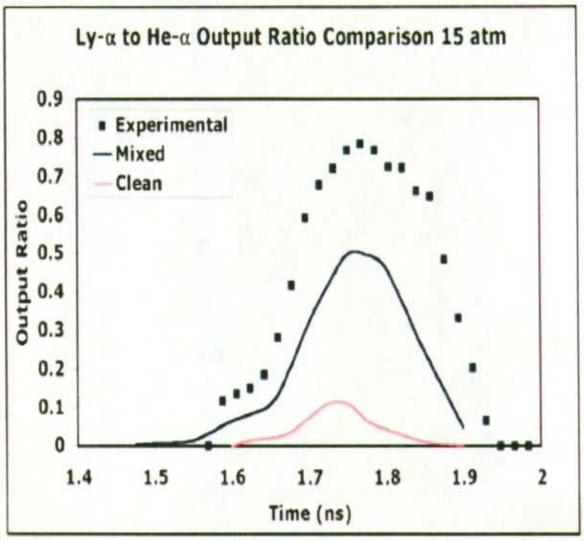

Fig. 4. This plot shows the comparison of the hydrogen-like to helium-like titanium alpha line energy output ratio for a clean calculation (red line), a calculation with mix (blue line), and the experimental values (blue squares). The simulations use mix parameter values of $\alpha = 0.09$ and $\delta = -1.0$.

One such source of data is the emissivity-averaged fuel ion temperature determined from the Doppler broadening of the neutron time of flight data. The data from the experimental implosions suggests fuel ion temperatures of 3.5 – 4.5 keV. The hydrodynamics simulations, however, were predicting temperatures of 2.2 – 2.6 keV for the both the clean and mix simulations with mix affecting the temperature by 100-200 eV at most. This suggests either a problem with experimental temperature measurements or a problem with the basic hydrodynamics simulation. Fortunately, charged particle data measurements (protons) can be used to resolve this issue. The ratio of the DD reaction rate (neutrons) to the D^3He reaction rate (protons) can be used as an independent indicator of ion temperature (Li, 2000), as is shown in Figure 5. The temperatures inferred from this ratio are consistent with the temperatures obtained by the neutron time of flight data in ICF capsule implosions. Thus, there appears to be a problem in the basic clean hydrodynamics simulation that potentially explains part of the difference in the line ratio comparison.

The other aspect of the ratio comparisons is the timing of the hydrogen-like alpha line emission. When comparing the simulation results with mix to the experimental data, we found that the emission of the hydrogen-like alpha line rises at about the same time and peaks at roughly the same time taking into account the discrepancy in the intensity. Note that this emission increases rapidly between 1.6 and 1.65 ns, roughly the time at which the reflected shock from the center hits the inner surface of the pusher. The reflected shock is believed to increase the instability of this interface as it is entering its deceleration phase up to maximum convergence.

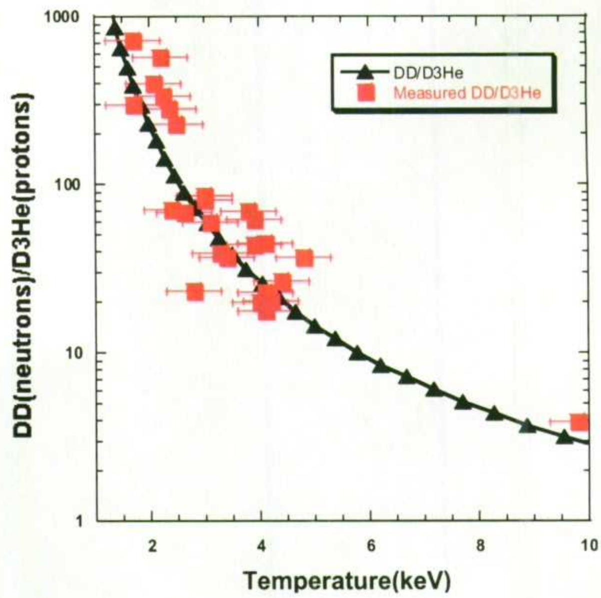

Fig. 5. This plot shows the comparison of temperatures inferred from the Doppler broadening of the neutron time of flight data to temperatures inferred from the ratio of the DD neutron to the D^3He proton yield for D_2 + ^3He filled capsules.

The XRFC's also proved to be a useful source of data for mix analysis. Figure 6(a) shows the first gated X-ray image where emission is observable from the imploding deuterium fuel. The gated X-ray image was set up with a 700 ps time differential between frames with a 63 ps separation between each image. With an uncertainty of about 50 ps in the timing of these images, the image showing the first X-ray emission occurs at about 1.6 to 1.65 ns and is consistent with the timing of the emission observed in the spectral emission data. Another aspect of the experimental data is the lack of limb brightening seen in the lineout of the experimental image shown in Figure 6(b). This is of interest because the radial lineout from the hydrodynamics simulation at the corresponding experimental time given in Figure 6(c) shows definite limb brightening. This could indicate that there is more mix at earlier times in the experiment than suggested in the simulation, although the under-prediction of the temperature could also be part of the reason for this difference.

4. CONCLUSIONS

The spectral emission data that we have collected so far has been very valuable in our analysis of the amount and especially the timing of pusher mix into the fuel core, and it has indicated potential problems in the simulation model currently being used that need to be addressed. The emission of the hydrogen-like titanium alpha line was more intense then predicted by the model, possibly suggesting that the mix model does not provide enough mix into the imploding fuel core. However, the temperature of the fuel core in the hydrodynamic simulation was 1.5 – 2.0 keV lower than experimentally indicated through the neutron time of flight data and could also have had a significant impact on the relative intensities the titanium alpha lines. This deviation between experimental and simulated temperatures will need to be addressed and resolved before we continue with our analysis of the Scannapieco and Cheng mix model.

It is our goal that the experimental data we gather from the experiment in September 2003 as well as the data gathered from upcoming experiments in September 2004 and the summer of 2005 will be utilized as a general data set to test out various mix models applied to the design of ICF capsules.

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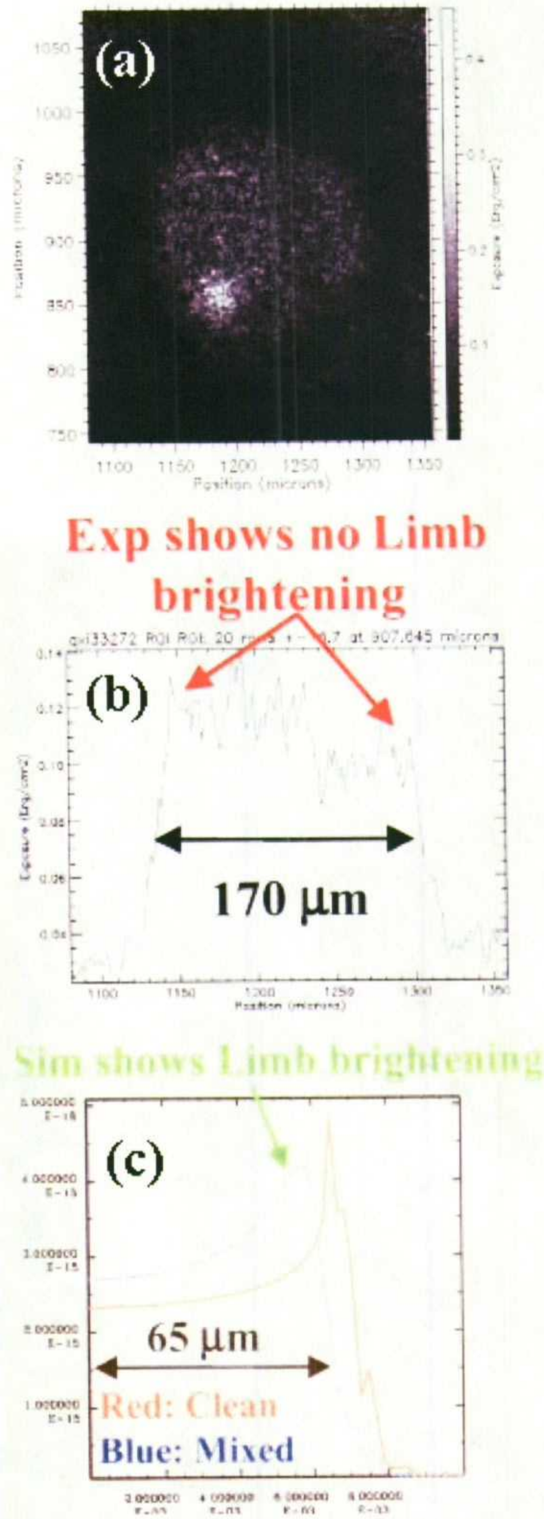

Fig. 6. The gated X-ray image (a) shows the first emission coming from the deuterium fuel, (b) is the intensity lineout across the diameter of the emitting fuel region, and (c) is a post-processed intensity lineout from the hydrodynamics simulation.

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